Engineering Resilient Cyber-Physical Systems

Future Grid Thrust Area 6 White Paper

Power Systems Engineering Research Center

Empowering Minds to Engineer
the Future Electric Energy System

Thrust Area 6 White Paper

Engineering Resilient Cyber-Physical Systems

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Executive Summary

At never before our modern lifestyle depends on a reliable supply of electricity. Brief power outages can be inconvenient and costly, while wide-scale blackouts lasting even a few days could rapidly become deadly. This thrust area considers various aspects of resiliency of the electric power grid. In short, a resilient power grid should be able to degrade gradually under increasing system stress, and then to return to its pre-disturbance condition when the disturbance is removed. The grid should be able to "keep the all the lights on" under small to moderate system disturbances, and to keep at least some level of system service even in the event of severe system disturbances.

Since the concept of electric grid resiliency is quite broad, especially with consideration of its associated cyber systems. Therefore a comprehensive coverage of this topic would be well beyond the resources of this thrust area. Rather, the thrust area presents focused research in three synergistic areas to help engineer a more resilient electric grid.

The first task considers how the electric grid needs to be engineered to deal with low frequency, but high consequence events with the initial focus on making the grid more resilient with respect to a severe geomagnetic disturbance (GMD). In several recent publications it has been a GMD event of magnitude similar to a magnetic storm that occurred in May 1921 could result in large-scale blackouts in which hundreds of high voltage transformers could be severely damaged, potentially crippling the electric grid for months. The focus of the task is to work with industry partners to develop techniques that allow power engineers to study the impact of GMDs on their systems, and to assist in the development of mitigation studies. Presently several utility studies are underway, along with an effort working in coordination with EPRI to study the GMD vulnerability of the entire North America Eastern and Western interconnects.

The second task is considering resiliency with respect to the mitigation of cascading failure risk. While the traditional n-1 reliability criterion inhibits most cascades, no grid is perfect and eventually some cascades will start and propagate. The degree to which the system can cascade provides a measure of system resilience. This task is developing methods of quantifying the resilience to cascading failure blackouts and showing how to maintain this resilience. Case studies will be used to allow engineers and policy makers to assess and react to some of the challenges of cascading failure blackouts.

The final task is investigating how increased system monitoring and control can be used to improve power grid resiliency due to loss of communication channels bringing in critical wide area measurements. With the recent national investment in phasor measurement unit (PMU) infrastructure, wide area measurement based control will become feasible. The resiliency of the physical electric grid will be critically dependent on the cyber infrastructure that handles the wide area measurements and the resiliency of the cyber infrastructure will significantly impact the resiliency of the physical electric grid.

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1 Introduction

The goal of this thrust area is to consider various aspects of resiliency of the electric power grid taking into consideration various components of the cyber systems that will be deployed, and viewing the interdependent system as a cyber physical system. While there are a number of different definitions for resiliency, probably the one most germane to electric grids is the "ability of a system to gradually degrade under increasing system stress, and then to return to its pre-disturbance condition when the disturbance is removed." A resilient power grid should not experience a sudden, catastrophic system collapse, but rather should be able to adapt to "keep the all the lights on" under small to moderate system disturbances, and to keep at least some level of system service even in the event of severe system disturbances.

Since the concept of electric grid resiliency is quite broad, especially with consideration of its associated cyber systems. Therefore a comprehensive coverage of this topic would be well beyond the resources of this thrust area. Rather, the thrust area presents focused research in three synergistic areas to help engineer a more resilient electric grid.

The first task considers how the electric grid needs to be engineered to deal with low frequency, but high consequence events. Of course, the electric grid can be subjected to many types of events that result in substantial loss of electric service. Examples include ice storms, tornados, hurricanes and earthquakes. And certainly for those affected, these are high consequence events. However there is another class of events that have the potential for even more catastrophic and long damage to the electric grid, identified by NERC/DOE in [1] as 1) cyber or physical coordinated attack, 2) pandemic, and 3) geomagnetic disturbance/electro-magnetic pulse.

Yet even within this field the scope is still quite broad, so the first task is initially focused on just one of these issues, the impact of a severe geomagnetic disturbance (GMD) on the electric grid. GMD electric grid impact has been the subject of several recent publications in which it is postulated that a GMD event of magnitude similar to a magnetic storm that occurred in May 1921 could result in large-scale blackouts in which hundreds of high voltage transformers could be severely damaged, potentially crippling the electric grid for months [2], [3], [4]. A storm in March 1989, which was much smaller than the one in 1921, resulted in a blackout of the entire province of Quebec, while a GMD in 1859 had electric field magnitudes estimated to be ten larger than the 1989 event.

To deal with this issue, a recent NERC report [5] provides a comprehensive discussion of the topic, along with several recommended follow on actions (in Section I.10). Research in this task is focused helping to better understand this issue, and in the application of tools to help with the development of mitigation strategies both in the planning and operations timeframes. That is, to make the system more resilient, to be able to adapt to deal with even a catastrophic GMD.

The second task will look at engineering resiliency with respect to mitigation of cascading failure risk. The traditional way to inhibit cascading failure is to inhibit the cascades starting with the n-1 criterion. Nevertheless, some cascades will start and propagate. The amount of cascade propagation after an initial failure is one measure of system resilience. Previous work has given new approaches to statistically quantify the amount of propagation from observed or simulated blackout data. The research objective with this task is to develop practical applications of these new approaches so that cascading failure risk can be quantified and mitigated.

The final task will investigate how increased system monitoring and control can be used to improve power grid resiliency due to loss of communication channels bringing in critical wide area measurements, from an operations point of view. With the large national investment in a wide area time-synchronized phasor measurement infrastructure, wide area measurement based control will become feasible. The resiliency of the physical electric grid will be critically dependent on the cyber infrastructure that handles the wide area measurements and the resiliency of the cyber infrastructure will significantly impact the resiliency of the physical electric grid.

With the increased uncertainty due to the large penetration of renewable resources, wide area measurement based control will be critically important to maintain the reliability and security of the physical grid. Any loss of the control signal due to disruption of the communication infrastructure could significantly affect the resiliency of the physical system. In order to enhance the resiliency of the interdependent cyber-physical system, two approaches can be pursued; 1) Build redundancy in the communication infrastructure or 2) Build redundancy in the physical system by developing a hierarchical control which utilizes alternate signals for control. The final task in this thrust area examines the latter approach and develops techniques to appropriately choose alternate control signals and design the controls robustly to perform satisfactorily with the alternate control signals if the optimal control signal is lost.

2 The Opportunities and the Challenges

In this section we consider the challenges and opportunities in each of these three tasks.

2.1 GMD Assessment: State of the Art, Major Challenges and Opportunities

The key challenge associated with dealing with all of the high impact, low frequency events identified in [1] is to determine the appropriate level of resources to devote to mitigating the impacts of events that by their definition are extremely low frequency, and in some cases may never occur. This is certainly the case with responding to GMDs, though the rather limited historical record (going back at most 155 years) indicates that a storm of the magnitude of the March 1989 event is probably likely soon, while one ten times as large (similar to the 1859 event) certainly cannot be ruled out.

Given the potential high impact of a GMD to the power grid, it is certainly an appropriate area for research. However, this research needs to be constrained (at least somewhat) by the recognition that because of its low frequency nature, extremely costly solutions are unlikely to be implemented.

Research into the impact of GMDs on the power grid goes back almost 40 years with [6] developing some of the key concepts and [7] showing how geomagnetically induced currents (GICs) could be presented in the power flow. As is described in [5], GICs are induced in the electric power grid when coronal mass ejections (CMEs) on the sun send charged particles towards the earth. These particles interact with the Earth's magnetic field causing what is known as a geomagnetic disturbance (GMD). So changes in the earth's magnetic field, usually expressed in nT/minute variation, produce electric field variations. These in turn give rise to quasi-dc (with frequencies much below 1 Hz) currents in long conducting paths such as pipelines, railways and the high voltage transmission grid.

In [8], it was demonstrated that the impacts of realistic GMDs on the power grid could be represented by dc voltage sources superimposed in each transmission line in the system, with the magnitude of the voltage determined by integrating the dot product of the electric field over the length of the transmission line. This is illustrated in Figure 2.1 for a simple system. How the GICs flow in the electric transmission system depends upon the induced dc voltage in the transmission lines and the resistance of the various system elements. Since the GICs are essentially dc, device reactance plays no role in their determination.

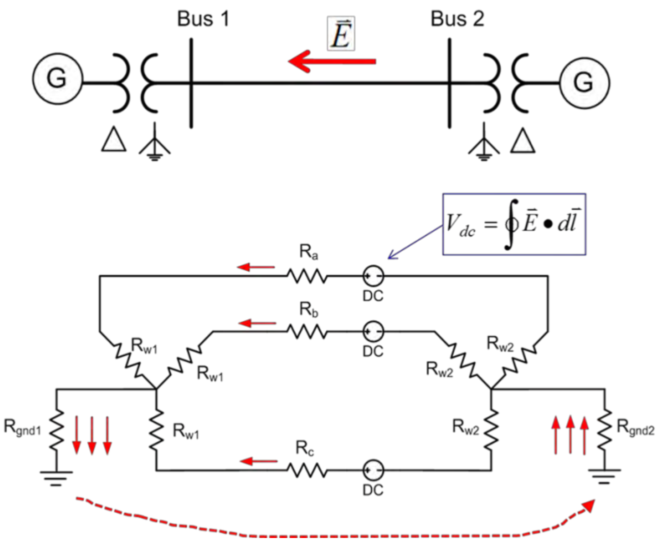

Figure 2.1: Representation of GICs in a Simple Power System

The impact of the GICs on the operation of the power grid is primarily due to the half-cycle saturation they cause in the transformers. For interested readers these impacts are well described in [5], particularly Chapter 8. The gist is this transformer saturation can create large amounts of harmonics, including even harmonics, which can cause transformer heating issues, relay misoperation, and capacitor/SVC/generator tripping. However, most germane to power flow analysis the half-cycle saturation causes an increased transformer reactive power loading [9], with widespread agreement that the increased reactive power loading varies linearly with the GIC flowing through the transformer. Hence a simple scaling constant can be used to couple the transformer GIC flow to the transformer's increased reactive power losses.

While it has been more than 30 years since power flow studies including the impact of GICs were first described in [7], there has been almost no published work looking at the impact of GICs on large power grids, and on the development of strategies to mitigate the impact of GICs. The work described in [3] certainly considers large systems, but seems to use a proprietary algorithm that makes duplication of the results difficult. Hence the recommendations from NERC in [5] for improved tools for GIC analysis and management. The research being pursued here to address this issue is described in the next chapter.

2.2 Operational and Planning Considerations for Resiliency: State of the Art, Major Challenges and Opportunities

The power system is being transformed and new solutions, systems and devices must be developed and applied. These solutions will move the power grid resilience and reliability further into uncharted territory and will increase the uncertainties in ensuring resilience and reliability. This increases the importance of assessing solutions for their impact on power system resilience and cascading failure blackouts. Any transformative technology that increases the frequency of large blackouts is likely to be shelved or severely restricted, regardless of its other merits, so it is essential to quantify and manage the risk of blackouts and generally keep the lights on as we transform the power system. It is fundamental to engineering resilience that the tendency for failures to propagate into a huge blackout must be limited.

More broadly, resilience includes the ability to withstand the initial failures, the limiting of cascading failures that cause or exacerbate the blackout, and the process of recovery and restoration. There is much known in risk analysis about the initial failures, and there is some useful experience and methods for power system restoration, but quantitative methods for cascading failure are only recently emerging. Therefore this task concentrates on quantifying cascading failure.

Detailed descriptions of cascading failure blackouts are extremely complicated and a brute force approach will fail due to a combinatorial explosion of rare events and rare interactions. Moreover, it is difficult to observe or generate with simulation enough data to reach statistically valid conclusions. This is because, although high impact, large blackouts are rare events. Moreover, blackout sizes do not have conventional statistics, but are observed to have “heavy tails” that indicate that extreme events, although rare, are expected to occur. Despite these challenges, the bulk statistical approach that we will pursue looks promising and could succeed in quantifying and mitigating the risk of cascading failure blackouts from both observed and simulated data. The bulk statistical approach should be seen as complementary to and supporting more detailed methods of analysis.

The traditional way to inhibit cascading failure is to inhibit the starting of cascades with the n-1 criterion. Nevertheless, and especially when the power system is stressed, some cascades will start and propagate. In a resilient power system, the cascade propagation is usually weak, cascades are likely to end quickly, and the risk of propagation to a large blackout is acceptably low. However, in a power system that lacks resilience, there is a significant risk of cascading to large blackouts. There is a trade-off in both planning and operations between fully utilizing the power transmission system and ensuring that the risk of cascading blackouts is acceptably low. We cannot rely on the generally high reliability of the past power system because the transforming power system has different stresses, uncertainties, and technological complexities overlaid on the previous power system. Quantifying the resilience to cascading failure blackouts and showing how to maintain this resilience in case studies will allow engineers and policy makers to assess and react to some of the challenges of cascading failure blackouts. We need to quantify the benefits (or problems caused) by proposed changes to the power system with simulation studies with methods that move beyond sampling some stressed cases. We also need to monitor the power system performance from observed data, especially since the state of the art in cascading failure simulations omits many mechanisms of cascading failure and makes many approximations.

One of the interesting project challenges is to communicate the results to a wide audience: power system engineers, academics, experts on infrastructure, policy makers, and the public.

2.3 Improved Power Grid Resiliency through Interactive System Control: State of the Art, Major Challenges and Opportunities

With increased penetration of renewable resources and the resulting uncertainty due to these resources, it is envisioned that the future grid will use a hierarchical set of synchronized measurements taking into account the performance of the associated communications networks to effectively deploy corrective control and increase grid resiliency. The hierarchy in the measurement set is based on the physical location of the measurement with regard to the location of the control actuation. These corrective control options would be critical for maintaining system reliability and resiliency. A critical element in determining the reliability of the wide area control scheme would be the reliability of the communication infrastructure that delivers the wide area control signal from the remote location where it is measured to the location where the controller is actuated. Any disruption in the communication infrastructure would lead to the wide area control actuation signal being unavailable and could result in a potential vulnerability since the desired control action could not be actuated.

Two broad classes of solutions could be developed to tackle wide area communication infrastructure failures; 1) The communication network could be built with greater redundancy to provide alternate communication paths for the same signal, 2) Greater redundancy could be incorporated in the wide area control scheme in which the control system could be designed with alternate control actuating signals if the primary control signal is unavailable due to communication failure. The specific task considered in this thrust area addresses the second class of solutions where a solution to the wide area communication infrastructure failure is addressed using an interactive systems control approach.

In the interactive control approach, the basis for the solution is to build resiliency in the control system and thus redundancy in the physical infrastructure rather than in the cyber system (the communication network) which interacts with the physical system. In terms of building resiliency in the control system, a simple but effective solution would consist of including alternate control actuation signals which would provide sufficient performance in terms of stabilizing the system but would not require the same communication channels. The control settings could then be designed using modern robust control techniques taking into account the alternate control actuation signals. Figure 2.2 illustrates the basic concept considering multiple control actuation signals.

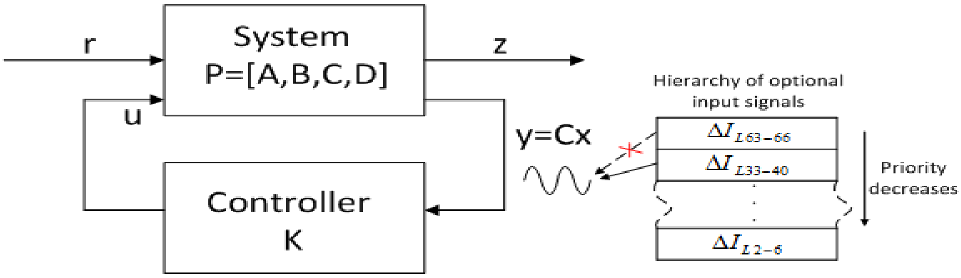

Figure 2.2: Control Design Based on Multiple Control Actuation Signals

In the envisioned setting the controller would be designed with candidate multiple control actuation signals. The signal that provides the best performance would normally be utilized. If however, there is a disruption in the communication channel delivering this signal, the next redundant control actuation signal which is available would be utilized. This would probably not provide the same performance as the signal that was lost but since the control settings were robustly designed the system would still perform adequately.

The approach considered is novel since it utilizes redundant control actuation signals and builds resiliency in the control design to account for disruption in the communication channels. In this manner, the inherent flexibility in the physical system is utilized to enhance the resiliency of the interdependent cyber physical system.

3 The Research Issues

This chapter describes the research that is being pursued in each of the thrust area tasks in order to achieve a more resilient cyber-physical infrastructure.

3.1 Task 1: Resiliency With Respect To Low Frequency, High Consequence Events

As described in the last chapter, the initial focus of this task is to perform research that seeks to better understand the impact of GMDs on the power grid, with the aim of developing mitigation strategies. The primary focus of the task will be considering the analysis of GICs on large systems. This will be done working with industrial partners including EPRI. As an example of the initial direction of this work, Figure 3.1 shows a visualization of how a GMD creating an electric field that varies from Northeast to Southwest across the North American Midwest could cause GIC flows. In the figure the color contour shows the assumed electric field intensity, while the yellow arrows show the direction and magnitude of the GICs.

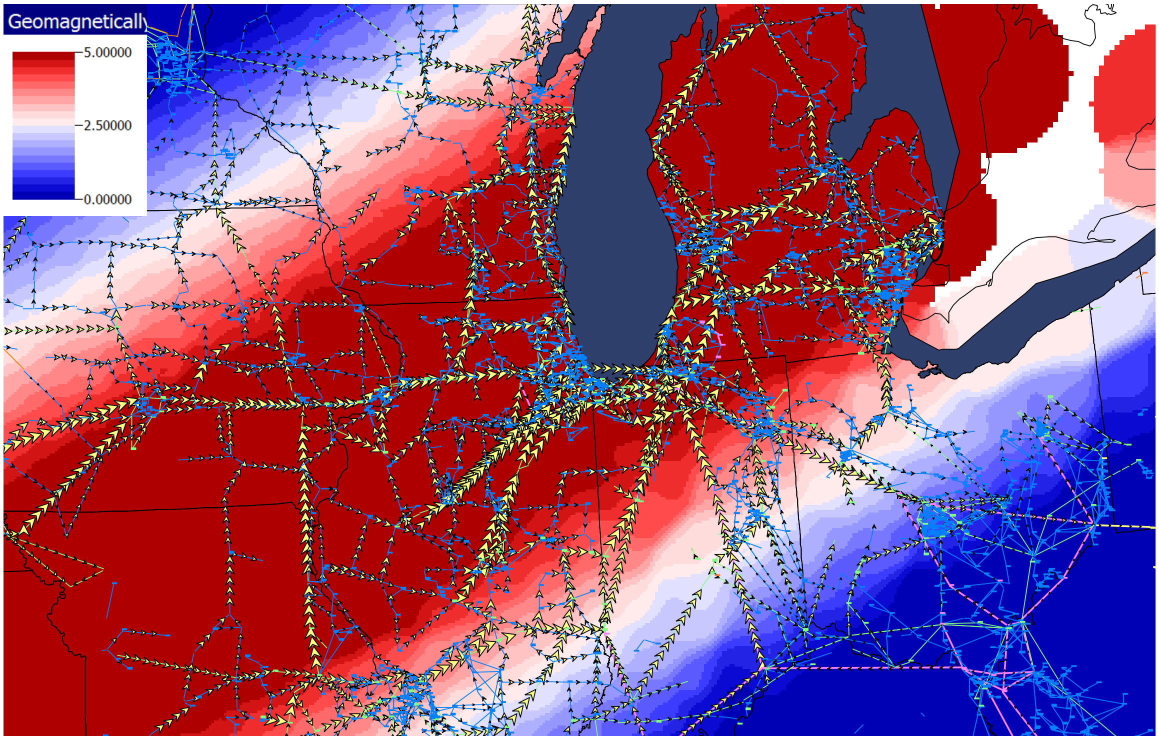

Figure 3.1: GIC Flow Visualization in a Large System Model

If the appropriate system parameters are known, the GIC flows can be calculated by just solving a set of spare linear equations that are computationally equivalent to solving for the bus voltages in a power flow. Hence the values can be determined in less than a second for systems with tens of thousands of buses. Once the GIC flows are known, the increased transformer reactive power loadings can be determined using a transformer specific linear scaling factor. Next, the full ac power flow can be solved including the impacts of GIC-induced increases in transformer reactive power consumption. Finally, with such a study methodology, the impacts of various mitigation options, such as installing GIC reduction devices (such as capacitors in the transformer neutral) and operational changes such as opening transmission lines.

To help to development this GMD mitigation, research will be pursued in the following areas:

1. Determination of how much precision is needed for GIC specific input parameters. While some of the parameters needed for the GIC calculations are included in standard power flow data sets, such as transmission line resistance, other values are not, such as substation grounding resistance. In order to perform large-scale GIC studies, estimates of these values are needed. An open research question is to determine which parameters dominant, and hence would require more precise determination. Also, an open research issue is whether the lower voltage portion of the transmission system (below 150 or 200 kV) can be neglected (as is suggested in [5]). Preliminary research indicates these lower voltage lines may contribute significantly to the GICs.
2. Related to the previous area is determination of the size of the transmission grid footprint needed for GIC studies. Since a key concern with the impact of the GICs on the power grid is a voltage collapse caused by increased transformer reactive power consumption, how much of the transmission grid needs to be considered in a GIC study is still an open question. Because reactive power doesn't tend to travel far in the high voltage grid, regional studies may be sufficient to determine the GIC impacts.
3. Development of algorithms to determine optimal mitigation strategies. Once the appropriate sized models are developed, this will allow for the creation of algorithms to aid in the determining appropriate mitigation strategies. For example, determining candidate locations for the installation of GIC reduction devices, or determining which transmission lines could be preemptively opened when a GMD is imminent. This research will also consider the impact of smart grid strategies for rapid load control.
4. Coordination with others such as EPRI and NERC in the development and testing of candidate GMD storm scenarios. This would involve determining how high the electric fields could become during candidate events, such as a "100 year storm." Also the level of detail in the modeling of the earth's conductivity needs to be considered.
5. Consideration of how changes in the nation's generation portfolio will impact GMD risk. The degree to which the augmentation of the existing transmission infrastructure to include new generation sources, such as large-scale wind farms, impacts the electric grid's GMD risk will be considered. Also, the impact of more local sources, such as rooftop PV, will also be considered.
6. Development of improved power flow solution techniques for systems with heavy reactive power loadings. Since GICs can greatly increase the reactive power

demands on the system, this can stress even normally robust power flow algorithms. Hence better solution techniques may need to be considered.

7. Development of improved techniques for GIC related model validation. Because of the infrequency of large-scale GMDs, there is currently a lack of actual system data associated with these events which is key to model validation. Nevertheless, there have been a number of smaller events in which data is available, and the number of data points is growing. Research in this area will seek to leverage existing measurements of the earth's magnetic field variation available in [10], with the growing number of measurements of power system values such as transformer dc neutral current and transformer reactive power consumption. Data sources may include the EPRI Sunburst Network [11] along with data from partner utilities which could certainly include PMU data.
8. Improved visualization of GIC flows. Presently power engineers to not have a good intuitive feel for how GICs would flow through their systems. This area will look to develop improved visualization methods to help give this understanding.

3.2 Task 2: Operational and Planning Considerations for Resiliency

The overall objective is to engineer power transmission system resilience to cascading failure blackouts. To develop methods to do this, we first need to quantify this resilience and then give examples to show how to do power system engineering that accounts for this resilience.

This leads to the objectives:

- Quantify resilience to cascading failure
- Perform case studies ensuring resilience to cascading failure or mitigating cascading risk

The approach to quantify resilience will describe the overall cascading failure process with high-level probabilistic models. The parameters of these models will include the amount of propagation in cascades of failures. Since a resilient system must limit the spread of failures to avoid collapsing in a large blackout, the average amount of cascade propagation after an initial failure is a measure of system resilience.

The proposed high-level probabilistic models are called branching processes. Branching processes have traditionally been successfully applied to cascading phenomena in many fields outside risk analysis, but their application to cascading in risk analysis is very recent [12], [13], [14], [15], and [16]. The objective is to refine, validate and apply branching process models for the risk analysis of cascading failure in power systems. The main parameters of the simplest branching processes describe the average size of the initial failures and their average tendency to propagate. These parameters can be estimated from cascading failure data that consists of a series of observed or simulated cascades. It is significant that the estimation can be done with a relatively small number of cascades compared with the brute force method of simply waiting a long time for enough cascades to be observed or simulated to give statistically valid estimates of their probability. For example, extracting a meaningful cascading parameter from one year of observed cascades in a large utility would be useful; extracting the same parameter by brute force empiricism by waiting 100 years for enough large blackouts to occur is not practical. We will refine and validate the statistical estimation methods and then use them to quantify the amount of propagation and the risk of large cascading blackouts. We will develop these approaches to make them practical applications.

We will develop two types of case studies and new engineering approaches that are driven by and support these case studies. The first type of case study will process observed cascading failure data, quantify its resilience, and determine whether there is undue risk of cascading failure. We will not fix the risk criterion, but instead show how example risk criteria could be applied. A second type of case study will process cascading failure data produced by cascading failure simulations, quantify its resilience, and examine the changes in resilience when simulated changes are made to the power system or its operation. This will show how to assess if a proposed change to the power system mitigates or degrades resilience to cascading blackouts.

3.3 Task 3: Improved Power Grid Resiliency through Interactive System Control

The primary research issues being addressed in this task include the following:

i. Formulation of a metric to identify alternative wide area control actuation signals which would meet the control performance objective

ii. Redundant design of the communication infrastructure to transmit identified control actuation signals through different routes

iii. Robust design of the control system to include the choice of identified control actuation signals

iv. Testing and implementation of the proposed control approach

v. Examine viability and applicability of the concept to cyber physical system applications in the electric grid at large

The proposed task has motivated the solution to the premise being examined via the example of a supplementary damping controller (SDC) in conjunction with a thyristor controlled series capacitor (TCSC). The SDC will be formulated and designed to damp inter area oscillations using wide area control signals. The selection of candidates for the control actuation signals is done using appropriate observability and controllability metrics. Once this choice is made, the signal at the top of the list is typically used to actuate the control and control design is optimized based on the selection of the signal at the top of the list.

The premise of the task is to examine the use of the other signals identified in the list in case the communication infrastructure transmitting the signal at the top of the list is disrupted to actuate the SDC. It is assumed that the other signals identified in the list are spatially distant from the signal identified at the top of the list and communication infrastructure that would transmit these signals is not affected by the disruption of the communication infrastructure associated with the signal at the top of the list. This assumption could also be incorporated in the metric which selects the alternate control actuating signals.

Once an alternate control actuating signal is identified, its ability to provide a similar control performance as the signal at the top of the list (lost as a result of communication system failure) would have to be ascertained. Instead of having to repeat this exercise for all candidate signals an approach based on modern robust control synthesis tools could be considered. In this approach, the choice of the candidate control actuating signals would first be made based on the metric developed. Instead of designing the control system for the control actuating signal at the top of the list, a robust control synthesis procedure utilizing either a H_∞-synthesis approach [17] or a μ-synthesis [18] approach would be applied to design the controller for multiple control actuating signals for a range of operating conditions. The performance of this controller could then be tested for the loss of the control signal at the top of the list by utilizing the control actuation signal which is next on the priority list. The approach envisioned is currently being tested on a realistic power system. The proposed approach if proven successful could be extended without loss of generality to other types of controllers. Figure 3.2 depicts an overview of the framework that will be utilized to robustly design the control settings.

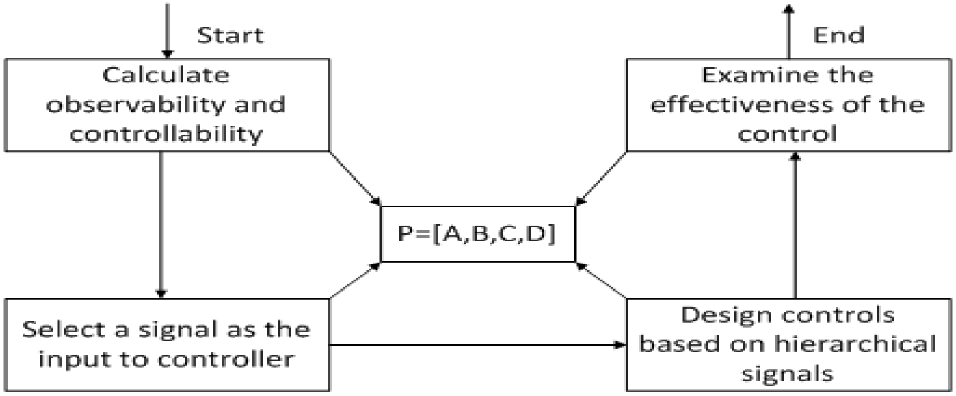

Figure 3.2: Overview of Robust Control Design Approach

4 The Future Grid and Conclusion

As our nation becomes even more dependent on a reliable supply of electricity, issues of grid resiliency will play an ever increasing role. The chilling scenario outlined at the beginning of [4], in which a large-scale GMD causes a massive planetary scale blackout with millions of fatalities and more than a trillion dollars of economic impact, is too significant to ignore. The future grid must be resilient enough even to deal with such a catastrophic event.

Resilience includes not only the ability of power system components to resist stresses and initial failures, but also the ability of the system to limit the propagation of outages cascading to cause widespread blackouts. To ensure resilience and be able to mitigate the risk of cascading outages, we need to develop practical ways to quantify the probability of cascading from observed and simulated outage data. The second project task will develop these practical applications. The future grid must contain new technology and new operational and planning procedures, and we need new approaches to be able to confirm that these innovations do not lead to cascading blackouts.

With the large investment in synchrophasor measurement capability and the development of fast communication capabilities, the use of wide area controls for enhancing the reliability of large electric grids is a distinct possibility in the near future. The concept of developing redundancy in the controls associated with the physical system as a means of enhancing system resiliency and reliability against failures in the communication infrastructure associated with wide area controls could provide an effective solution to harden the system.

In thrust area we can currently pursuing research to help achieve such a resilient cyber-physical infrastructure. The first task is considering how to make the system more resilient to a potential “game-changing” scenario of a large scale GMD. Enhanced algorithms and validation will help the industry prepare beforehand, both in the planning and operations timeframes for dealing with this event. The second task is considering ways in which improved understanding of how systems cascade can result in a more resilient system design. The concept proposed in the last task provides a solution which is unique and could be applied to several aspects of control in the electric grid.

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